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Direct writing of 40nm features inside fused silica glass with oscillator ultra-fast lasers

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ABSTRACT

With ultra-fast oscillator lasers (less than 1nJ/pulse, 80MHz repetition rate), we propose that we could fabricate features with less than 40nm inside UV transparent material such as fused silica and quartz. The low threshold property of this demonstration could lower the cost of lasers, and improve the throughput of laser machining due to the quasi-CW nature of the laser used. Our initial results shows that damages are observed with threshold as low as 1nJ before the UV objective, and then size is below 1 micron.

Keywords: Ultra-fast, laser, fused, silica, glass, 40nm feature, direct writing

INTRODUCTION

Recently, laser induced breakdown (LIB) by ultra-fast laser pulses are found to be able to create 3D features inside silica materials[1,2,3,4]. However, because the laser wavelength is at 800nm or 400nm, multiple photon process has to be applied and therefore amplified ultra-fast laser pulses have to be used when machining inside UV transparent material, such as fused silica. Such requirement on amplified laser sources raises the initial cost --- cost of an amplified ultra-fast laser is >$200k while cost for oscillator is about $100k. The amplified laser pulses also slow down the processing speed due to the limited repetition rate --- amplified lasers usually have repetition rate about 10s kHz or less, while oscillator lasers have quasi-CW 10s of MHz repetition rate. In such experiments, for ~120fs long laser pulses, often over μJ pulse energy is required to create the feature. The peak power is often well over 10^{14}W/cm^2. The ratio between the diffraction limit and the feature resolution is close to one, due to excessive heat generated from multi-photon absorption.

The first mature technology for writing features is the direct UV laser writing, e.g. UV laser writing grating in fibers. For example Fiber Bragg Grating (FBG) writing in fibers. One of the disadvantages of FBG writing with conventional UV source is the need of the specially treated silica fibers (doped with hydrogen or other rare earth elements to increase induced change in refractive index Δn), instead of directly writing on glass fibers because conventional UV light absorbs much less in regular lightly Ge doped silica glass fibers and the resulting refractive index change is much smaller. This means special fiber has to be added in the fiber optic network and the fusing of different fibers creates unwanted loss in the fiber optic network. Here, our setup could directly write on normal lightly Ge doped, or even undoped silica glass fibers, saving lots of troubles and optical losses. The resolution of the proposed technique is also much better than diffraction limit at the UV wavelength, therefore allows direct writing of any photonic bandgap structure without the use of a UV transmitting mask, which is very expensive ($10k/ea).

Although multiple-beam scanning inside the silica could create 3D features, it has two inherent disadvantages. First, the feature resolution is decided by the diffraction limit of the optical beams, even with deep UV laser beams, the best feature resolution has to be close to a micron or even larger. Such resolution might be good enough for long wavelength operation, but certainly not good enough to create photonic crystal structures for UV/visible wavelength. Second, the requirement of the overlap of more than one beam result in difficulty in creating complex 3D features, as the feature already created will disturb the second beam's propagation.

The second mature technology uses the processes in IC manufacturing, such as Chemical Vapor Deposition (CVD), electron beam lithography and etching processes. Doped silica or totally different material (e.g. GaAs) features are

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created this way inside silica material. In optical communication and information processing, for example, the current planar lightwave circuits (PLC, e.g. arrayed waveguide, AWG) are manufactured using CVD process followed by etching and CVD process again. This CVD process although can be scaled to very high capacity, requires expensive CVD, optical photo mask patterning and chemical etching machines. This makes prototype cost very high and development cycle very long. Also the material used in such PLC is based on silica which has very high thermal expansion (~10^{-5}/°C), therefore to make a thermally stabilized device, either actively temperature stabilization or silicone material, which has negative thermal expansion, has to be used in between as compensation. This makes the PLC devices very expensive to implement. However, if we could use ultra-fast laser to create similar waveguide pattern in fused silica glass at high speed, then we could avoid the use of expensive machines, cut down on prototype cost and time cycle, this is particularly true if only an ultra-fast laser oscillator is required (cost is less than $100k), like we proposed in this work. Also, by using fused silica, which has thermal expansion ($0.5x10^{-6}$/°C) more than an order of magnitude smaller than silica formed in CVD process, we could reduce the thermal effects at minimal cost (e.g. NTT Electronic's athermalized AWG device has reduced the thermal expansion of silica by an order of magnitude).

TECHNICAL PRINCIPLE

The principle of this work, machining in silica material with ultra-fast UV lasers, is based on two photon absorption (TPA) instead of multi-photon (>2 photons) absorption in the LIB process as described in the beginning of this work.

TPA has already been used in biological microscopy [5], and also recently in the micro-machining in UV cured polymers[6]. Features created with TPA with IR laser beams are approaching 100nm in resolution and comes with high aspect ratio [8]. Such TPA process uses ultra-fast lasers without chirped amplifier, this means the pulse energy is below nJ level and the peak power is around 10^{12}W/cm^2 or less. The ratio between the diffraction limit of the focus (~800nm) and the final feature resolution (~120nm) is about 7.

Silica material are transparent to UV light, e.g. at 266nm. But, silica absorbs strongly, i.e. totally blocks, in the VUV wavelength, i.e. the harmonic of 266nm at 133nm. If one uses intense ultra-fast IR laser pulses, e.g. 800nm, hoping to create multiple photon absorption (MPA) at 133nm, then the electromagnetic field needed will be much higher than LIB threshold, creating LIB before MPA. The resolution of LIB, although on the scale of a micron, is much larger than the resolution of MPA could create. By using ultra-fast UV laser pulses, much weaker electromagnetic field is needed before the TPA cross section is strong enough to happen, thus catastrophic LIB could be avoided. If this true, then much lower cost is possible for nano scale machining in silica materials.

Here the localized densification as a result of TPA around the focal point of the focusing ultra-fast laser could be estimated.

The absorbed pulse energy due to TPA process can be approximately calculated by,

$$\alpha = \beta * I * L / (1+\beta * I * L), \quad (1)$$

where α is the ratio of the absorbed pulse energy to the input pulse energy, β is the TPA coefficient, I is the input laser intensity, and L is the depth of focus of the laser in the focal region. For a 100 fs pulse at 266 nm with 1 nJ pulse energy and focal diameter of 2r = 0.25 μm (e.g. a lens and beam with NA of 0.8 could be used), the instant intensity at the focal point will be $2x10^{13}$ W/cm^2. In the L = 0.5 μm focal region, the absorbed energy by TPA is 2% and 28% of the input pulse energy for the fused silica (β=$2x10^{-11}$ W/cm^2) and the Ge-doped fused silica (β= $42x10^{-11}$ W/cm^2), respectively [β data from Dragomir et.al., 2002]. Then, the density of the TPA excited electrons in the focal region ($V=\pi r^2 L$) could be as high as $1.6x10^{21}$cm^{-3} and $2.2x10^{22}$cm^{-3} for the fused silica and the Ge-doped fused silica, respectively. The highly excited and tightly localized free-carrier plasma state may expand very rapidly, generating a hollow core surrounded by a denser phase[9, 10]. The change of refractive index is mainly decided by the change of density [12]. Consequently, the permanent structure and refractive index changes will be formed in the tightly localized focal region. Compared to the density of SiO_2 in fused silica ($3x10^{22}$cm^{-3}) the density of the TPA excited electrons generated by a single laser pulse (1 *nJ*) is quite

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significant. Only 2 pulses for the Ge-doped fused silica and 20 pulses for the fused silica are needed to excite one electron from each SiO_2 in the focal region. We will expect the high efficiency of the TPA fabrication for the high laser repetition rate (e.g. 76 MHz).

Or, if the amount of absorbed energy is just converted into heat, the resulting temperature rise could also be calculated. For fused silica, the Cp is 0.77J/g/K and the density is 2.2g/cm3, the temperature rise due to absorbed energy from each pulse in the tiny volume is

$$(1\ \text{nJ} * 2\%) / [(0.77\text{J/g/K}) \times (2.2\ \text{g/cm}^3) \times (0.25\mu\text{m})\text{^}2 \times 3.14 / 4 \times 0.5\mu\text{m}] \approx 500\ \text{K} \quad (2)$$

each pulse could result in 500K of temperature rise in the highly localized area in silica!

We also expect the efficiency of the TPA fabrication will be even higher using shorter wavelength since the TPA coefficient is larger at shorter wavelength. Obviously by tuning the pulse energy, exposure time at a fixed point and the fabricating laser wavelength, one could finely control the change of index, the size of the feature being fabricated as well as the speed of fabrication.

Due to the highly nonlinear dependence on laser power density, the processing cross section of the laser beam is much narrower than the Gaussian beam width, which can result in processing resolution even below the diffraction limit. Compared to the ~120nm feature resolution achieved with 800nm IR wavelength, our 266nm wavelength should be able to create even finer feature resolutions, e.g. **~40nm**!

Table 1. Comparision of different fabrication techniques for PLC circuits

	Cost	Limitation on material	Processing speed	Prototype cost & cycle	Feature resolution
IC processes derived technique	High, >$millions on hardware	No, but crystaline silica will be formed	High,	High and turn around cycle is long	100nm or finer, cost goes up fast w/ finer resolution
UV laser (cw, ns)	Low, $50k~$100k	Doped silica material	High	Fast, but some require expensive mask	Submicron or worse
Chirp-Amplified fs laser pulses	Relatively low ~$200k	No limitation	Limited by repetition rate	Fast, and no need for mask or expensive setup	Submicron
TPA UV sub nJ/pulse fs laser	Low, <$100k	No limitation	Quasi-CW pulses give high speed	Fast, and no need for mask or expensive setup	Around 40nm?

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The table above summarizes the features of currently available techniques as well as this proposed TPA UV laser technique for writing waveguide and photonic crystal structures inside silica

EXPERIMENT

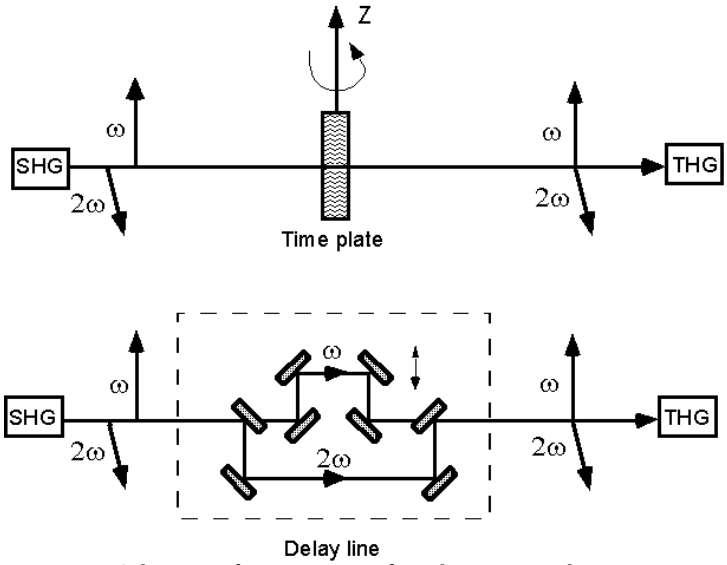

Figure 1. Schematics for generation of UV harmonic with Timeplate technology v.s. traditional delay line technology

In order to use deep UV ultra-fast lasers in nano fabrication, ultra-stable harmonic generators to efficiently convert the fundamental of Ti:Sapphire laser into deep UV are needed. We have already constructed ultra-stable and compact harmonic generators with our patented TimePlate technology (US Patent 5,852,620) for utlra-fast laser oscillators. In this setup, automatic spatial and temporal overlap are realized simultaneously by using a compensation Timeplate instead of an optical delay line, saving lots of extra optics and also improve the ease of operation and stability significantly. So ultra-fast UV laser pulses could be stably generated for industrial applications. Typical efficiency of tripling with this system is >15% with 1W of 120fs laser pulses at 80MHz repetition rate and 800nm, resulting about 2nJ of UV pulse energy. The system is very compact --- 6”(h) x11”(l) x6” (w), which could be held in hand. Such compact size is only possible with the Timeplate design, because the traditional delay line design involves much more complicated procedures --- separation of the second harmonic and the fundamental, and let them pass through different delay line and then recombine them. The traditional delay line design makes the system very large and the adjustment very sensitive because one has to ensure the overlap in both time and spatial domain when try to mix the second harmonic with the fundamental. The compact size of the Timeplate tripler enables it to work perfectly with the ever smaller ultra-fast laser oscillators based on diode pumped fiber laser systems. The pulse width is about 170fs at 266nm.

We use an UV objective lens with a NA of 0.8, to focus the 266nm beam into a fused silica glass plate. We observed change of refractive index, i.e., the expanding laser beam has distorted shape from uniform circular shape if there is change of refractive index inside focal point area. We observe the center part of the expanding beam has reduced intensity when such damage happens. With only 1nJ input before the objective at 266nm,we start to observe the damage inside the glass. The time required to see the change is as short as 1ms, as decided by chopping the beam input at 800nm before it is sent into the TimePlate tripler and then the UV objective. This corresponds to 80,000 laser pulses with the oscillator is operating at 80MHz. We are trying to use electronic shutter and fast moving glass plate to decide the shortest duration needed for observing such damages. We are also trying to use SEM to verify the dimensions of the damaged area inside the fused silica glass.

We could already verify that the damage has submicron feature dimensions. When we observe the damage, we then lower the input energy/power of the UV light, and then we move the focal spot away from the damaged spot and observe the disappearance of the distortion of the expanding laser beam. The distance of the displacement required to observe such disappearance of distortion is less a micron.

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CONCLUSION

We propose that ultra-fast UV laser pulses with nJ pulse energy could direct write 40nm features inside UV transparent materials. We observed such damages at nJ pulse energy level, and the technology is mature for application with the Timeplate tripling design for UV harmonic conversion.

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